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Art VII.—*Experiments on Manganese Deficiency Disease ("Grey Speck") of Cereals.*

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Introduction.

In a previous paper (2) the writer described some experiments on manganese deficiency (or "grey speck") disease of cereals. The present paper deals with further work on the same subject extending over five years. A short account is first given of the present state of knowledge with regard to this disease.

Many important crops are liable to this disease, including wheat, barley, and especially oats. The soils on which crops are affected—here called "deficient soils"—have a pH value of at least 6.5, usually over 7.0. The disease may be overcome by lowering the pH of the soil below 6.5, by adding a compound of manganese to the soil, or by spraying the affected plants with a solution of a manganese salt. Descriptions of the symptoms, various experiments in the field, and descriptions of some deficient soils are referred to in (2). Since deficient soils often contain normal quantities of total manganese, the deficiency must be due to a very low availability of that manganese.

It appears that the forms of manganese in the soil which take part in chemical reactions are firstly the bivalent ion, mostly attached to the colloids as exchangeable manganese; and secondly, higher oxides of manganese, which range from highly active to relatively inert forms. The only evidence as to the chemical composition of the higher oxides has been provided by Naftel (3) whose work favours the formula Mn_2O_3 which should probably therefore replace the former conventional formula MnO_2. The writer has suggested that this Mn_2O_3 may be divided into four fractions in order of activity according to arbitrary tests. The most reactive fraction (*a*) can oxidize the organic matter of the soil at pH 2; the next fraction (*b*) can oxidize quinol at pH 7; fraction (*c*) can oxidize hydrosulphite but not quinol at pH 7, while (*d*) is still less active. It was further suggested that plants can utilize only the bivalent ion and fractions (*a*) and (*b*) of Mn_2O_3. In neutral or alkaline soils if aeration is good, the bivalent ion is mostly changed into the higher oxides, and it appears that then the health of sensitive plants such as oats depends on the presence of appreciable quantities of manganic oxide in forms (*a*) and (*b*). Healthy alkaline soils contain over 100 parts per million of manganese in this reactive form, while deficient soils have less than 25 parts. It appears that waterlogging, which has been successful in pot tests, cures the disease by reducing some of the manganic oxide to the bivalent state, after which it reverts under normal drainage to more reactive forms of manganic oxide; soluble manganese compounds when added to deficient soil are transformed into reactive forms of manganic oxide and so may remain available even though insoluble, while compounds which acidify the soil restore bivalent manganese permanently to the system and so cure the deficiency.

This report deals only with results obtained in plot and pot tests, with a review of the relative values of various methods of treating the soil in order to overcome the trouble. It is hoped that further chemical experiments concerning the forms and transformations of manganese in the soil may be published at a later date. The introductory account that has just been given is inadequate and some of the theory will probably have to be modified, but it will serve as a background for the experiments on plants that are recorded here.

The possible treatments of the disease are:—

(*a*) Thorough acidification of the soil with sulphur or otherwise.

(*b*) Addition of ammonium sulphate at or about the time of sowing. (This is equivalent to a minor and local acidification of the soil.)

(*c*) Addition of soluble or easily available compounds of manganese with the seed.

(*d*) Spraying the crop with dilute manganese sulphate as soon as symptoms of deficiency occur.

(*e*) Waterlogging for two or three weeks before sowing.

(*f*) Sterilizing the soil with formalin or some other suitable compound.

Of these methods, treatment with sulphur has already been shown to overcome the deficiency disease and to give better results with wheat than even large additions of manganese. In Europe and North America, however, where large areas of soil are deficient, little use has been made of sulphur, and the only acidic material used is ammonium sulphate, which would often be used in any case as a source of nitrogen. A comparison of sulphur and ammonium sulphate has therefore been made in plot experiments to be described. Method (*c*)—addition of soluble compounds of manganese with the seed—always increases the yield of both straw and grain, and is the only practicable method on highly calcareous soils, such as that of Corny Point, South Australia, where barley is sown (5) with a manganiferous superphosphate drilled in with the seed. Method (*d*)—the use of manganese sulphate as a spray—causes a spectacular recovery of sick plants, though two or three sprayings may be needed. Methods (*c*) and (*f*) can be tried only in pot tests; the former (waterlogging) has been included in this work, but not the latter (sterilizing) which, however, has given spectacular results in the hands of Gerretsen (1).

Plot Experiments in 1934 to 1938.

Experiments were carried out in these years on the same plots as in 1932–3; the results of the earlier experiments have been reported (2). The soil is a grey sandy loam with 0.2 per cent. $CaCO_3$ and of surface pH about 7.5, uniform in texture to a depth of eighteen inches and overlying a yellow clay. The surface soil has not been developed in situ and probably consists of sweepings from the roads of crushed basalt which formerly served Melbourne. Twenty plots each of one square yard are available so that five treatments can be replicated four times. Experimental errors are inevitably large on such small plots, but differences between treatments are often highly significant in spite of this, and the same differences occur again in subsequent years, thus greatly increasing the significance of the results. In previous years, in which wheat had been grown continuously, the best yields were found on the four plots which had been brought by sulphur to a pH of 6.0 to 6.5. Twelve other plots had been left alkaline and had been given $MnSO_4$ in various ways. The addition of manganese always led to yields higher than the controls though residual effects one year after application were poor.

Plot Experiments in 1934.

Experiments in 1934 were designed partly to confirm previous results, partly to compare the effects of ammonium salts with nitrates as a source of nitrogen on this soil. The plots were treated as follows:—the control plots (A), the sulphured plots (B), and the plots (C) that had been most heavily treated with manganese in the two previous years (4 cwt. per acre $MnSO_4$ crystals), were sown with 2 cwt. superphosphate and 260 lb. $NaNO_3$; of the two other sets of plots, those given $MnSO_4$ with the seed in 1933 (D) were again given 1 cwt. per acre $MnSO_4$ crystals with the seed, as well as the same superphosphate and nitrate as the controls, while the plots tested for residual effect of manganese in 1933 (E) were given 2 cwt. superphosphate and 200 lb. ammonium sulphate. In this way all plots were given equal amounts of nitrogen.

Free Gallipoli wheat was sown on May 22nd, during a very dry spell which lasted for three weeks longer. Germination was slow and patchy on all the plots given $NaNO_3$, but was normal and uniform on the four plots given ammonium sulphate. These plots (E) were outstanding throughout the winter, both in colour and in height. They had also produced the greatest number of tillers on October 3rd, when tillers on the other plots fell in the same order as in 1933, i.e., the $MnSO_4$ plots (D) were superior to the controls (though barely significantly) while the sulphured plots (B) again showed no increase over the controls; the tillers of (B) were, however, decidedly strong, and the total weight of the crop at this stage could not have been so much in favour of (E) compared with (B) as the tiller count indicates.

On October 10th there began a two-month spell of exceptionally wet weather, during which thirteen inches of rain fell, thus prolonging the growing season. However, the effects of sulphur and manganese were the same as in more normal years. The sulphured plots performed far better than any others during October and November, excelling in survival rate of tillers to ears, and especially in the weight of grain per ear. The $MnSO_4$ plots (D) also showed high figures for these values. The ammonium sulphate plots, however, fell right back and produced comparatively poor ears. There was a heavy incidence of foot-rot (*Ophiobolus graminis*) on all the alkaline plots, including a considerable amount even on the manganese-treated plots (D) where the plants were free from manganese deficiency disease and would have been expected to be more resistant. The acidic plots, however, were fairly free from disease.

The results of this year's work (Table I.) confirm those of former years. It is interesting to notice the all-round superiority of this year's manganese (D) over residual manganese (C); although in fact the soil of (C) contained 33 per cent. more added manganese than (D), this added manganese in plots (C) had evidently become much less available by the winter of 1934. The approximate equality of (B) and (D) is similar to what was found in 1932, but is in contrast to the marked superiority of sulphur over added manganese in 1933.

Table I.—Free Gallipoli Wheat, 1934.

—	Tillers.		Ears.			Grain.	
	Per Plant.	Per Sq. Yd.	Per Sq. Yd.	Percentage Surviving.	Gm. per Ear.	Bushel per Acre. Mean.	Bushel per Acre. Range.
A. Control	2·93	225	105	47	0·58	10·9	7·8–14·6
B. Sulphur	3·24	223	**158**	**71**	**1·16**	**32·6**	26·7–41·6
C. $MnSO_4$, Residual ..	3·00	233	127	55	0·75	**17·0**	16·2–18·1
D. $MnSO_4$ with seed ..	3·13	264	**183**	**69**	**0·94**	**30·5**	29·5–32·0
E. Am_2SO_4	**3·46**	**300**	**174**	**58**	0·51	15·7	11·2–21·5

Standard error of mean of four plots, 1·88 bushels per acre.
Figures significantly different from control are in black.

The most interesting result, however, is the comparison of thorough acidification (B) with the use of ammonium sulphate (E). This comparison gives opposite results according as the crop is cut in the spring or grown for grain. It should be noted that the conditions are weighted in favour of (E), which had received a dressing of $MnSO_4$ two years before; this residual manganese should be made available by the ammonium sulphate more easily than the rest of the soil's manganese. In spite of this, the plants of (E) deteriorated during the last two months of growth.

PLOT EXPERIMENTS IN 1935.

Since the wheat had suffered badly in 1934 from *Ophiobolus,* the experimental crop chosen in 1935 was Algerian oats. Experiments were designed to answer the following problems:—

1. Manganese deficiency has been dealt with either by keeping the soil alkaline and adding soluble manganese at sowing, or by acidifying the soil without adding any manganese. The latter method produces a healthier, and in some years a bigger crop of grain than does the former, but tillering on the acidified plots has shown no increase over the control plots and has been markedly below that of the alkaline plots to which $MnSO_4$ was added. This behaviour may be due to a difference in the forms in which manganese exists in the soil, or else to a general effect connected with pH and lime status. This could be tested by comparing the two treatments, (*a*) sulphur alone, and (*b*) sulphur with $MnSO_4$ at sowing.

2. The residual effect of a previous treatment with $MnSO_4$ has been shown (2) to be strikingly small. The author suggested that this was due to the completeness of precipitation of the added manganese in the surface inch or two of soil; and chemical analysis showed that this precipitation had in fact taken place. Information on the effect of thorough mixing of the surface ten inches of soil should settle this issue.

3. It would be useful to confirm the conclusions of 1934 regarding the inferiority of an ordinary dressing of ammonium sulphate to a heavy sulphuring.

The twenty plots were divided as before into five groups each of four replications, as follows:—

A. Control, no manganese added at any time.

B. Sulphured in 1932 and 1933, no manganese added at any time.

C. Alkaline, given 4 cwt. per acre $MnSO_4$ in 1932–1933. These were thoroughly mixed to a depth of ten inches just before sowing, but no more manganese was added.

D. Alkaline, given 1 cwt. per acre $MnSO_4$ in each year, 1932–3–4. Not dug at any time.

E. Given 1 cwt. $MnSO_4$ in 1932 and made acidic with excess sulphur in 1935. 56 lb. per acre $MnSO_4$ crystals added with seed in 1935.

Plots A, B, C, and E were sown with superphosphate and sodium nitrate; plots D were sown with superphosphate and ammonium sulphate. The total amount of nitrogen (48 lb. per acre) was the same for each plot. The first of the problems mentioned above should be solved by comparing B with E, the second by comparing C with A and D, the third by comparing D with B and E.

The seed was put in in the last week of May. Germination was uniformly good. As in 1934, the plants that had been given their nitrogen as ammonium sulphate showed a better colour and were taller during the early stages of growth. Some of the plants of group E, however (sulphur and $MnSO_4$), made poor growth at first, and many leaves showed a red colour at the tip. A few of the worst affected plants on these plots remained stunted to the end of the experiment, but the majority recovered, as described below. These toxic symptoms were evidently due to the unintentionally high acidity of the soil, which had a mean pH of 4.3 over the surface six inches; the added manganese probably made conditions worse.

The symptoms of grey-speck (manganese deficiency) became marked by 21st July—an earlier date than had been noticed for wheat, which is less sensitive than oats. The affected areas included all the alkaline plots (A, C, D) and patches on the previously sulphured plots (B). These bad patches had a mean pH value of 6.8, while healthy patches on the same plots had a mean pH of 5.7—a correlation with pH that has often been noticed elsewhere. By the end of August, the plants of treatment C (residual manganese, dug in) were somewhat healthier than those of treatment D (residual manganese, not dug in); these in turn were rather better than the controls (A). During September, however, all the plants on these twelve alkaline plots (A, C, D) died, and during October their place was taken by a vigorous growth of Wimmera rye-grass (*Lolium subulatum*) together with other plants, notably *Phalaris minor, Briza minor,* and *Vicia sativa.*

Grain-bearing heads were confined to the plants of treatment E (which recovered very well from their earlier poisoning), and to the more acidic patches of treatment B. The yield of the former plots was 60 per cent. above that of the latter. Since only five of the eight sulphured plots were uniformly free from grey-speck, the results do not provide a clear answer to the first of the three problems at the beginning of this section, concerning the reason for the low tillering of wheat on the sulphured plots, though it seems likely that pH is the main factor. The inferiority of ammonium sulphate to sulphur is again strikingly confirmed, while the failure of the plots that had been thoroughly dug shows that the absence of a good residual effect of manganese sulphate cannot be due, as the author suggested, to a lack of mixing of the surface layers with the rest of the soil, but must be due to a change in the nature of the manganese compounds concerned.

PLOT EXPERIMENTS IN 1936.

The work of previous years has shown that the addition of large amounts of manganese to the soil here studied has only a slight residual effect in the years after the application, even if the soil is thoroughly mixed to a depth of eight inches or so. On the other hand, the addition of 80 parts per million of manganese in the form of "active" manganic oxide has made it possible for oats to grow healthily on the highly-deficient soil from Mount Gambier in the second year after application (see below). A waterlogging of two weeks also has kept a pot of Mount Gambier soil healthy for four years at least, after the waterlogging. It is of interest therefore, to try to find out whether extremely heavy applications of manganese compounds will restore the University soil permanently to a state in which it will grow healthy oats or wheat. In 1936, besides confirmatory tests with sulphur and ammonium sulphate, the further treatments were tried of 12 grams per square yard of manganese as freshly precipitated MnO_2 (or about 60 p.p.m. Mn) well mixed with the surface six inches of soil, and the incorporation into a plot of about 50 Kg. of the soil of the same plot which had had three weeks' waterlogging in a pot. Neither of these treatments succeeded in overcoming the disease of the oats.

The plants on the strongly acidic soil looked poor during June and July, but later made excellent growth. The plants given ammonium sulphate developed "grey speck" during the first warm days of August, and steadily deteriorated thereafter. The only plants which yielded well were those on the acidic soil and those given $MnSO_4$ with the seed, the former being significantly better. The effect of manganese deficiency is so much more acute on oats than on wheat that the sulphured plots are already far superior to controls when tillers are counted, though the manganese-treated, alkaline plots produce rather more tillers than the sulphured plots.

Another treatment which was tried on other plots and which proved futile was a heavy dressing of blood manure (which contains very little manganese and differs in this respect from farmyard manure). In another experiment four plots were sown with seed which had been soaked for two days in 0.1 per cent. $KMnO_4$ and was deeply stained with MnO_2. The plants on these plots were decidedly healthier than controls or manured plots during the winter and until the end of August, but collapsed with the first warm days of spring and finally produced only insignificant amounts of grain.

PLOT EXPERIMENTS IN 1937.

While it appears that oats do not benefit from any residual effect of added manganese compounds on this soil, it is possible that the less sensitive wheat plant may do so. Wheat was therefore tried this year, and the plots that had been heavily treated with manganese dioxide or mixed with previously waterlogged soil were compared with those on which $MnSO_4$ was applied with the seed. At the same time a new line of inquiry was made. A few European workers have claimed that a heavy dressing of quicklime improves the growth of oats on deficient soils. Since this suggests that there is an upper limit of pH, as well as a lower limit, to the incidence of "grey speck" disease, the problem may best be approached by adding alkaline material to bring the pH well above 8, preferably to about 9. Four plots which had never received additional manganese but had been sulphured some years before (Plots B of 1934) were treated with caustic soda at the rate of about 2 tons per acre.

The growth on the acid plots (pH 4.5–5.0) was the same as usual; there were fewer tillers in September than on the control plots, but the survival rate was very high (87 per cent.) and the average weight of the ears was much higher than on any other plots, so that the final yield was the best, though the difference between the acidic plots and the manganese-treated plots is not significant. (The figures here tabulated refer to the weight of the whole ear and not of the separated grain.) The residual effect of a heavy application of manganese compounds two years previously appears to come close to that of an application of $MnSO_4$ with the seed—a result in marked contrast to that obtained with oats. Finally the caustic soda had such a bad effect on the soil that both germination and subsequent growth were very poor. Results are collected in Table II.

TABLE II.—GHURKA WHEAT, 1937.

Treatment.	Tillers.		Ears.			Total Yield Gm. per Sq. Yd.
	Per Plant.	Per Sq. Yd.	Per Sq. Yd.	Percentage Surviving.	Gm. per Ear.	
A. Control	2·06	167	125	75	0·82	103
B. Caustic soda	1·93	44	28	64	0·86	24
C. $MnSO_4$, Residual	2·27	179	132	74	1·19	**157**
D. $MnSO_4$, with seed	2·16	180	148	82	1·26	**186**
E. Acidic	2·00	142	123	87	1·64	**202**

Standard error of mean of total yield, 15·5 gm.
Yields significantly greater than control are in black.

Plot Experiments in 1938.

These experiments were designed with two main ends in view. Firstly, it was desirable to repeat the previous year's experiment with caustic soda under more favourable conditions for germination, and this was achieved by digging gypsum into the surface layers shortly before seeding. Secondly, it would be interesting to compare the growth of plants on soil that has been acidified or given some other improving treatment, with the growth of plants which are sprayed with a soluble manganese salt as soon as the symptoms of deficiency occur, but which otherwise grow on "deficient" soil.

The plots this year comprised:—(A). Soil untreated but plants sprayed with 1 per cent. $MnSO_4$ as soon as deficiency shows; (B). Highly alkaline, treated with gypsum; (C). and (D). Slightly alkaline, residual manganese only; (E). Highly acidic. This arrangement left the plots without the conventional "controls." However, the "residual manganese" plots could be relied on to give very low yields with which the others could profitably be compared. The oat variety Dawn was sown, and calcium nitrate was added to all plots at the rate of 1 cwt. per acre. The symptoms of grey speck appeared about the middle of August. The plants of group (A) were sprayed with a fine spray of 1 per cent. $MnSO_4$ (so as to ensure that every leaf was wetted) on 16th and again on 26th August. The plants immediately recovered, and the symptoms did not reappear. The highly alkaline plots at this time showed surprisingly good growth, with as healthy a colour as those on the acid soil.

When the tillers were counted early in October the acidic and highly alkaline plots were outstanding (see Table III.). However, the latter plots were very patchy, with some healthy plants and some sick. Samples of surface soil taken under healthy plants had a pH of 8.5 to 8.7, while samples around the sick plants had a pH of about 7.5.

Table III.—Dawn Oats, 1938.

Treatment.	Tillers.	Ears.		Grain.		Total Yield
	Per Sq. Yd.	Per Sq. Yd.	Percentage Surviving.	Gm. per Ear.	Gm. per Sq. Yd.	Gm. per Sq. Yd.
A. Sprayed	151	**114**	**76**	0·61	**70**	**312**
B. Caustic soda	**213**	**99**	46	0·56	54	**294**
C. Residual Mn	132	51	38	0·33	17	105
D. Residual Mn	139	70	50	0·47	33	152
E. Acidic	**196**	**147***	**75**	0·82	**120***	**463***

Figures significantly greater than "controls" (C) are in black.
Those significantly the greatest in the column are also asterisked.

The spring was very dry and warm, no rain of importance falling after early August, and the grain ripened in late November. As the figures show, the acidic plots gave the usual high survival of tillers to grain-bearing heads and a high yield of grain per head. The sprayed plants also showed a good survival of tillers but a relatively poor yield of grain. This no doubt was due to the fact that the primordia had already suffered from manganese deficiency before the symptoms of "grey speck" appeared. The soda-treated plots did not fulfil their earlier promise; but the final yield included a number of large plants bearing much grain (from the most alkaline patches) besides a greater number of typically "deficient" plants.

Summary and Discussion of Plot Experiments.

The results up to date may be summed up as follows:—

Oats.

1. *Acidification of the soil with sulphur* to below pH 6.5 gives the highest yields both of straw and of grain, and its superiority over the controls appears in the middle of August.

2. *Application of ammonium sulphate* with the seed causes somewhat increased vegetative growth during June and July only, and thereafter has no advantage over controls which have been given nitrogen as nitrate.

3. *Alkalinization of the soil with caustic soda* causes a marked improvement, especially in vegetative growth up to the end of September. This improvement appears to depend on raising the pH of the soil over 8.5.

4. *Application of manganese sulphate* with the seed causes an increase in tillering (24 per cent. in one case) but the survival of tillers to heads and the final yield are less than on acidic plots. The optimum application of manganese sulphate has not been tested, but the routine rate in these experiments was 1 cwt. of the crystalline salt per acre.

5. *The residual effect* of manganese compounds applied to this soil in the preceding year is slight.

6. *Spraying plants with $MnSO_4$* as soon as they develop symptoms of "grey speck" causes immediate improvement, but both the tillering and the yield of grain are low in consequence of the deficiency during the first two months of growth.

7. *The incorporation of blood manure* into the soil is useless.

Wheat.

1. *Acidification of the soil with sulphur* to below pH 6.5 causes rather poorer growth than on the control plots during the winter months, and a slight depression in tillering. In late September, however, the tillers are strong, and the plants on acid soil have

a better colour from that time on. Survival of tillers to ears and weight of grain per ear are high, and the final yield is better than is obtained with any other treatment.

2. *Application of ammonium sulphate* with the seed causes much better winter growth and a greater production of tillers in late September, than any other treatment; the total weight at this time, however, may not be greater than with other successful treatments. The survival of the tillers to ears and the production of grain per ear are poor, and the final yield is little better than on the controls.

3. *Application of manganese sulphate* with the seed causes an increase in tillering, up to 30 per cent. compared with controls, but the survival of tillers to ears and the weight of grain per head, though superior to controls, are less good than on acidic plots, and the final yield of grain is never greater and is sometimes less than on the acidic plots.

4. *The residual effect* of manganese compounds applied in moderate amounts to this soil in the preceding year is marked, though it is less than that of a fresh application. However, a heavy application of freshly precipitated manganese oxide, well mixed with the top eight inches of soil, appears to exert a residual effect as good as that of a fresh application.

These results may be compared with those of Townsend and Wedgworth (6) who grew French beans (*Phaseolus vulgaris*) on a highly-deficient soil consisting of burned peat, and studied both the immediate and the residual effect of adding sulphur or manganese sulphate to the soil. They found that heavy applications of manganese sulphate (100 lb. per acre) did immediate good, but this good effect could hardly be seen in the succeeding crop. Light applications of sulphur (5 cwt. per acre), which were insufficient to bring the pH into the acid region, had a good effect which was only temporary. A heavy application of sulphur which brought the pH down to 6.0 appeared to do lasting good, although its immediate effect was to depress the yield. It appears that some intermediate product of oxidation such as thiosulphate, may be responsible both for the temporary good effect of small amounts of sulphur (due to its reducing action) and for the temporary bad effect of larger amounts (due to direct toxicity). A spray of dilute manganous sulphate led to excellent vegetative growth; but these workers did not compare the various treatments with regard to reproductive growth.

Pot Tests.

Pot tests carried on during the last five years have been directed to two ends, namely, attempting to cure deficient soils, and attempting to make healthy soils deficient by heavy liming.

Experiments with Deficient Soils.

The former work has been especially concerned with the soil from Mount Gambier (South Australia), where Samuel and Piper (4) made the first Australian studies of manganese deficiency in the field. This soil is a deep, permeable sandy loam, derived from basaltic ash, and highly immature. Manganese deficiency of cereals occurs on this soil type in places where the reaction is neutral or alkaline; the free calcium carbonate which is responsible for the alkalinity may be derived from the layers of Tertiary limestone through which the volcanic ash burst its way. The various treatments that have been attempted on a calcareous sample of this soil are described below. In every experiment a sensitive variety of oats was the test plant, viz., Algerian or Dawn for winter and spring, and Tasmanian White Oats for early summer. The pots are 3 feet high and hold 25 Kg. of soil.

(1) Acidification to a pH value of 6.5 or less. This brings about a complete cure, as was reported by Samuel and Piper (4). Such treatment is of little practical value, since huge amounts of acid are needed to destroy the free calcium carbonate.

(2) Addition of a manganese compound, uniformly mixed with the whole of the soil in the pot so far as to ensure that the roots reach the manganese. Two pots were used here, one of which was given crystalline manganese sulphate and the other freshly prepared "active" manganese dioxide, completely free of water-soluble manganese. The $MnSO_4$ was added at the rate of twenty parts of manganese per million of soil, and the MnO_2 at the rate of 80 parts. This was done in October, 1934. The plants on the treated pots made excellent growth during the next two months, while the two controls suffered severely from grey speck (part of this experiment was reported in a previous paper). At least one crop of oats has been grown on these pots in each year since then, and the plants have always done much better than the controls, which regularly succumb to grey speck. Slight symptons of manganese deficiency have occasionally been noted on the leaves of the pot that was given manganese dioxide, but the plants have always recovered later. Evidently the long-term residual effect of added manganese on this soil is far more marked than on the University soil. No reason for such a difference can be suggested, but the relative importance of various stages in the cycle of biological and non-biological changes through which manganese moves must differ from one soil to another. There remains, of course, the possibility that interactions with other elements may be involved.

(3) Prolonged waterlogging. When the pots were prepared in October, 1934, the outlet from one pot was closed and water was added so as to stand about an inch above the level of the soil. After four weeks of waterlogging, drainage was restored. Very sick oat plants were immediately transplanted into this

pot, and they proceeded to make excellent growth. The subsequent history of this pot has been remarkable; with no addition of manganese at any time and with normal drainage (which is naturally very free on this soil) six healthy crops of oats have been grown. On one occasion only, during a hot spell in December, 1937, a few leaves showed slight symptoms of grey speck; but there were no symptoms in 1938.

It appears therefore that a single waterlogging has brought about a lasting cure. This soil normally contains a large reserve of manganic oxide just below the level of availability to plants (2, p. 250), and the waterlogging has apparently promoted some of this reserve to a more available state. Oat plants growing on this pot contained the high figure of 54 parts of manganese per million in 1935. Unfortunately, this cure does not seem to be a practicable one in the field. The winter rainfall at Mount Gambier is heavy, averaging 12 inches from June to August inclusive, but this water soaks quickly through the soil. One plausible method of inducing waterlogging in the field would be to make the soil highly alkaline with sodium carbonate or hydroxide and to rely on the hydrophilic properties of the resultant sodium clay to cause waterlogging during the winter. The soil would naturally have to be reclaimed later with gypsum. A preliminary experiment was done in 1938 to test this idea; 56 gm. of crystals of sodium carbonate was added to a pot of Mount Gambier soil, and water equivalent to about an inch of rain added every four days during August and September. The oats which were sown in the next month succumbed very quickly to manganese deficiency; this was not surprising, since the soil did not approach to a waterlogged condition during the period of treatment.

Pot tests were also carried on with a gravelly soil from the southern wheatbelt of Western Australia. This soil contains about 50 per cent. of ironstone pebbles about half an inch to an inch in diameter, and is of low fertility, apart from its manganese deficiency. The incorporation of freshly precipitated manganese dioxide into the pot of this soil greatly improved the growth of oats as compared with the control; a still better result was obtained by a fortnight's waterlogging, the results of which have persisted for two years.

The University soil was also waterlogged in a pot for three weeks, but the plants which subsequently grew on this soil suffered from manganese deficiency. It is surprising that the treatment which was so successful with two deficient sandy soils should fail with a third.

Attempts to Make Healthy Soils Deficient.

The author suggested previously that an extraction with a solution of quinol in normal ammonium acetate at pH 7 might serve to determine the amount of available manganese in a soil, and that podzolic soils containing not more than 25 parts of such manganese per million might become "deficient" on liming to pH 7 or beyond. Tests in small pots have since been carried out, and they tend to confirm the above suggestion. The following figures (Table IV.) relate to the properties of certain soils from Southern Victoria; the "available" manganese is that which is extracted in the cold by normal ammonium acetate together with that which is extracted by a 0.2 per cent. solution of quinol in normal ammonium acetate. All the soils are podzolic and derived from sedimentary material, except the University soil. The Bellarine soil has been included for comparison, though it was not used for pot tests; this sample was taken from land adjoining an area on which oats had suffered from manganese deficiency following heavy liming several years earlier.

Table IV.—Soils Tested for Effect of Heavy Liming.

—	Description and Location of Soil.					
	Light Grey Sandy Loam, Timboon.	Grey Fine Sandy Loam, Coleraine.	Grey Sandy Loam, University.	Grey Sandy Loam, Bellarine.	Grey Sand, Cranbourne.	Grey Sandy Loam, Narre Warren.
pH	5·3	5·8	5·0	5·4	3·4	5·6
Available Manganese p.p.m.	1	17	15	8	2	7

The treatments consisted of varying applications of calcium carbonate, the heaviest of which brought the pH of the soil above seven in each case. The experimental plant was oats, either Dawn or Algerian, and all pots were given an adequate supply of calcium nitrate and potassium phosphate.

1. *Timboon Soil.*—The plants on the alkaline pots suffered severely from manganese deficiency; this occurred as soon as the soil had been made alkaline.

2. *Coleraine.*—The first result of heavy liming was to cause greater growth on this soil, though symptoms of manganese deficiency also appeared. Three years after liming, the plants suffered severely from deficiency.

3. *University.*—The soil from some garden beds, which have never been limed, is the same in origin as that on which the experimental plots are now located. The first year after heavy liming, the oats made better growth than on the acid soil, but in the second year they succumbed to manganese deficiency.

4. *Cranbourne.*—This is an extremely poor soil which must be limed before ordinary crops will grow well on it. Overliming, however, immediately brings about symptoms of deficiency.

5. *Narre Warren.*—During the twelve months which have passed since samples of this soil were brought to pH 7.3 in pots, improved growth has been the only result of liming.

From these experiments it appears that a considerable time must elapse before certain soils with a fair original reserve of available manganese are adversely affected by liming to above pH 7, but where the reserve is low, deficiency appears soon after the lime is applied.

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